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(54) **Solid-state display with reference pixel**

(57) A system for controlling a digital image display device having addressable pixels on a substrate, the pixels having performance attributes, and a control circuit for controlling the pixels of the display device, including: a reference pixel located on the substrate and connected to the control circuit, the reference pixel having the same performance attributes as the pixels in the display; a measurement circuit connected to the reference pixel to produce an output signal representative of the performance attributes of the reference pixel; an analysis circuit connected to the measurement circuit to receive the output signal, compare the performance attributes with predetermined performance attributes, and produce a feedback signal in response thereto; and the control circuit being adapted to receive the feedback signal and control the digital solid-state display device in response thereto.

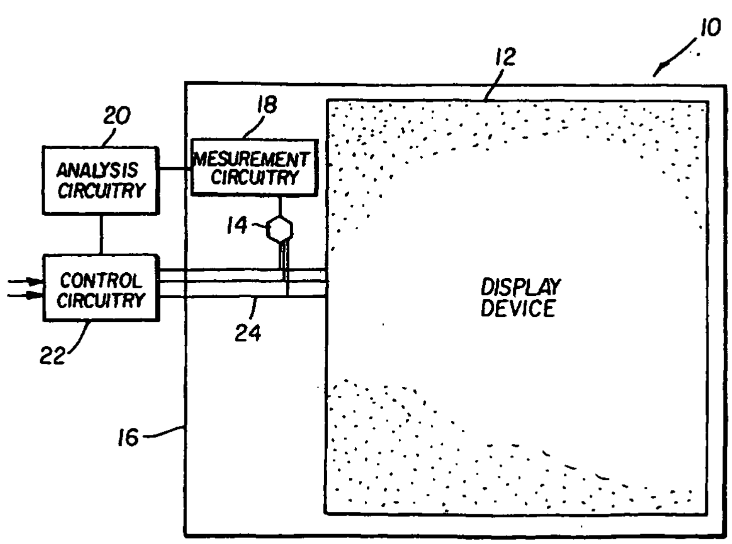

FIG. 1

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Description

[0001] The present invention relates to solid-state display devices and more particularly to such display devices having means to optimize the display through the use of feedback information from the display.

[0002] Solid-state image display devices are well known and widely available. These devices rely upon a variety of technologies such as liquid crystal displays, plasma discharge, and light emitting diodes, both organic and inorganic. Each type of device has its own peculiar set of characteristics and its own set of difficulties depending on the nature of the technology and the manufacturing method and materials utilized in its production.

[0003] The characteristics of a solid-state image display are affected not only by its inherent technology and by the manufacturing processes and materials used to create it, but also by the way in which it is operated. The voltages supplied to the device, current available, the timing of various signal lines, etc. all affect the display characteristics. Typically, the optimum parameters for the device are specified to the system integrators using the device and the system is designed to those specifications.

[0004] Unfortunately, over time the characteristics of any display device can change. These changes can occur over a very short period of time (milliseconds) or over years. For example, when charge is stored at a pixel, the charge decays, affecting the brightness or color of the pixel. Alternatively, as time passes and a display device is used, the nature of the pixel can change: transistors become less efficient or responsive, impurities creep into display elements causing them to decrease in brightness or change in color, etc.

[0005] To some extent these changes can be ameliorated by modifying the operation of the device. For example, image information can be rewritten (refreshed) at each pixel site, operating voltages can be adjusted, more current can be made available, the timing of the control signals can be modified, data value to charge ratios can be changed, etc. However, a typical system has no way to detect the performance changes or to modify the control parameters of the system. Hence, the quality and accuracy of the image display degrades and there is a need for an improved control system for digital image display devices.

[0006] Generally, image display devices suffer from problems associated with display refresh inefficiency that wastes power or requires expensive circuitry, and problems associated with aging that affect the color, brightness, and efficiency of the display. Additionally, organic light emitting diode (OLED) displays exhibit different power efficiencies for different colors, requiring special circuitry to obtain accurate color rendition. Moreover, the pixels in OLED displays emit light in proportion to the current passed through them. Current control circuitry is difficult and complex to implement. It is much easier and more convenient to control voltage in systems. It would therefore be useful to have a system in which the light emitted from an OLED display is accurately controlled with voltage control rather than current control circuitry.

[0007] OLED display devices generally operate by applying various voltages to power the device together with signal and data control voltages. Typically, the devices are organized so that a two-dimensional array of display pixels, each with its own address and data storage, emit or cause light to be emitted, thus creating an image. The control signals are carefully timed and act to store information (generally represented as charge) at each pixel. This information controls the attributes of the light displayed from that pixel, typically color and brightness.

[0008] Attempts have been made in the prior art to optimize particular display systems to overcome some of the problems noted above. For example, U.S. Patent No. 5,216,504 issued June 1, 1993 to Webb et al., entitled ***Automatic Precision Video Monitor Alignment System*** describes a digital control device within a video monitor to calibrate or otherwise optimize the display, either with human input or under automated computer control.

[0009] Some systems integrate user-controlled control mechanisms to provide more flexible operation or optimal use under varying conditions. For example, brightness and contrast controls are often available on video and LCD display devices. These controls can be based on information from the device itself, using a reference pixel within the display. U.S. Patent No. 5,157,525 issued October 20, 1992 to Eaton et al., describes the use of a reference pixel with separate control to maintain a pre-selected value for contrast or absolute brightness using a feedback arrangement which includes an LCD reference element. The feedback information is determined by measuring the average transmissivity of the LCD material with a photo-detector. One problem with the approach disclosed by Eaton et al. is that the control device does not directly respond to the operating characteristics of the pixels themselves, or address problems with different types (e.g. colors) of pixels within a display. There is a need therefore for an improved control system for controlling the output of an OLED display.

[0010] The need is met according to the present invention by providing a system for controlling a digital image display device having addressable pixels on a substrate, the pixels having performance attributes, and a control circuit for controlling the pixels of the display device, that includes: a reference pixel located on the substrate and connected to the control circuit, the reference pixel having the same performance attributes as the pixels in the display; a measurement circuit connected to the reference pixel to produce an output signal representative of the performance attributes of the reference pixel; an analysis circuit connected to the measurement

circuit to receive the output signal, compare the performance attributes with predetermined performance attributes, and produce a feedback signal in response thereto; and the control circuit being adapted to receive the feedback signal and control the digital solid-state display device in response thereto.

[0011] The advantages of this invention are a digital image display device with improved performance. By integrating reference pixels that provide a means to measure performance and feedback logic to control the operational characteristics of the display device, improved lifetime, better brightness, uniformity, color fidelity, power consumption, and persistence can all be achieved.

Fig. 1 is a schematic diagram of a display device with a reference pixel, measurement, analysis and feedback control circuitry;
Fig. 2 is a schematic diagram of a display device with multiple reference pixels, measurement, analysis and feedback control circuitry; and
Fig. 3 is a schematic diagram of a display device with a reference pixel with a current source according to the present invention.

[0012] The present invention creates a display device that overcomes the problems in the prior art through the use of reference pixels to enable the measurement of pixel performance and a feedback mechanism responsive to the measured pixel performance to modify the operating characteristics of the display device. These operational changes improve the performance of the display device.

[0013] The solid-state image display device with a reference pixel is composed of a standard, solid-state display device having an array or collection of pixels supplemented by an additional reference pixel or pixels that have the same performance attributes as the pixels in the display device. According to a preferred embodiment of the invention, the pixels are OLEDs having a local charge storage mechanism and a transistor drive circuit activated by the stored charge for applying power to each pixel. The reference pixels are not used as part of the display and need not be seen by a viewer. The reference pixels can be instrumented with a variety of performance measuring circuitry. The measurement circuit is connected to an analysis circuit that produces a feedback signal which is in turn supplied to a control circuit that controls the operation of the display device.

[0014] Fig. 1 illustrates the invention. A system **10** includes a display device **12** with an additional reference pixel **14** on a common substrate **16**. The characteristics of the reference pixel **14** are measured by a measurement circuit **18** and the information gathered thereby is connected to an analysis circuit **20**. The analysis circuit produces a feedback signal that is supplied to a control circuit **22**. The control circuit modifies the operating characteristics of the image display through the control lines **24**. Note that for clarity, the various elements are not shown to scale. In actual practice, the reference pixels **14** would be far smaller than the display device, as would the measurement circuit **18**.

[0015] The image display device **12** is conventional. Control signals, power, etc. are all connected as is well-known in the art, with the addition that the control circuit **22** can modify the control and power signal in response to the feedback signal. The system **10** operates as follows. When the display is energized and information is written to the display, thereby causing the display to display an image, the reference pixel is likewise energized in a known manner (for example one half, or full on) by the control circuit **22**. The energy, control, and information written to the reference pixel **14** is chosen to represent the performance of the display device **12** insofar as is possible. In particular, the reference pixel **14** could be operated in such a way as to represent an average pixel or a worst-case pixel, depending on the desires of the system designer. Those aspects of the system design of the most concern or having the worst performance might be carefully recreated in the reference pixel.

[0016] Once the reference pixel **14** is operational, the measurement circuit 18 operates and measures the pixel's performance attributes. The actual attributes measured will depend on the technology of the display device, the materials that comprise it and the manufacturing process used to create it. In particular, the charge storage at the pixel site, the impedance across any light-emitting pixel, the efficiency and frequency of the light emission, current draw, and voltage drop at particular points in a circuit, are all important attributes of the pixel performance.

[0017] The measurement circuit **18** monitors the performance of the reference pixel **14**. The measured performance values are compared to the expected or desired performance by the analysis circuit **20**. These comparisons can be based on *a priori* knowledge of the characteristics of the device or simply compared to some arbitrary value empirically shown to give good performance.
In either case, once a determination is made that the performance of the device needs to be modified, the analysis circuitry signals the feedback and control mechanism that initiates the change.

[0018] Care should be taken to ensure that the operational changes are kept within sensible bounds and that uncontrolled positive feedback does not occur. For example, if brightness declines over time and increased voltage improves brightness, some limit to the possible voltage applied to the device should be set to prevent dangerous or damaging conditions from occurring. Moreover, it is only useful to measure those attributes and control those operational mechanisms that are effective in modifying the performance of the device.

[0019] In addition to the single reference pixel shown in Fig. 1, a plurality of reference pixels could be used (see Fig. 2). For example the pixels in the display device **12** can include colored subpixels; if the operational or

display characteristics of the various colored sub-pixels differ, it can be useful to include a reference pixel **40**, **42**, **44** corresponding to each color. Indeed, one can generally include a reference pixel for each type of pixel or for each specific attribute for which a measurement is desired. The measurement and operational approach described is identical in these cases but the feedback correction is applied only to those pixels of the corresponding type.

[0020] Multiple, identical reference pixels can be used as well. This will provide a wider variety of measurements and their various results can be combined to provide an overall feedback signal less subject to noise, process variation, failure, and so on. It is also possible to have reference pixels associated with specific portions of the display or to use actual display pixels as reference pixels. It is also possible to have a plurality of reference pixels and associated measurement circuits, wherein each measurement circuit measures a different performance attribute.

[0021] The measurement and analysis circuitry can be integrated directly onto the same substrate as the display device or it can be implemented externally to the display. In general, higher performance and greater accuracy can be achieved by integrating the circuitry directly with the reference pixels but this may not be desirable for all display devices. (For example, the pixel technology and manufacturing process may inhibit the integration of measurement circuitry and logic.)

[0022] This concept can be extended to the analysis and even the feedback control circuitry. These may also be integrated in various ways on the display device itself. System issues such as power, the implementation of control and timing logic, etc., and the effective integration of the various functions in the system will dictate the best approach.

[0023] Not only can a properly instrumented reference pixel provide feedback in support of operational changes that accommodate changes in the pixels over time, it can also be used to modify the technique used to control the brightness of the display. In particular, the light output by organic LED devices depends directly on the current through the OLED. As current changes, the light output changes. Unfortunately, current regulation within a solid-state electronic device is much more difficult to achieve than voltage regulation. Hence, a display mechanism that relies upon voltage control is preferred and will reduce design costs and increase the pixel fill factor (reducing the area needed for transistors). This preferred approach can be achieved through the use of a reference pixel. By measuring the impedance across a reference pixel at a given voltage, the current can be compared to the desired current. By modifying the voltage, the impedance and hence current can be modified until it meets the desired level.

[0024] The feedback system shown in Fig. 3 provides the effect of current regulation while implementing voltage regulation by adjusting the voltage to meet the desired current through the pixels. A current measurement circuit **26** implements the generic measurement circuit **18** of Fig. 1. The control circuitry **24** of Fig. 1 is divided into two parts, the voltage signal **28** applied to the reference pixel (the power signal) and the data and select lines **30** (the control signals) applied to the reference pixel. This current measurement circuit **26** measures the current passing through the reference pixel **14** as a function of the voltage and control signals. The current measurement and voltage value is transferred to the analysis circuit **20** through signal **32**. The analysis circuit compares the voltage and current to its desired values for the pixel and adjusts the voltage signal **28** through the control circuitry **22**. The desired values can be obtained from a table relating desired current to pixel value. Alternatively, a behavioral model for the pixel can be utilized to provide the desired current value and consequent voltage adjustment. This same adjusted voltage is then applied to all of the pixels in the display device. In effect, the use of feedback from a reference pixel enables an appropriately compensated voltage driven display that operates with the benefits of current regulation. Thus, a higher quality current regulated imaging display device can be manufactured at the lower cost of a voltage driven device.

[0025] If multiple reference pixels with different attributes are used, as in Fig. 2, a separate measurement circuit is used to compensate the voltage appropriately either with a single compromise voltage or with a separate control for each type of pixel. As described above, the measurement circuit, in this case the current measurement circuit, could be resident on the same substrate as the reference pixel or not.

[0026] This approach to controlling organic LED displays extends to compensation for aging properties as well. As the organic materials age, the current required to maintain a certain level of brightness increases and the impedance (for a given brightness) increases. Compensation for this effect can be achieved through an increased voltage, mediated through the measured impedance as described above. Hence, this invention can serve to ameliorate the negative effect of aging materials within an organic LED display.

[0027] Note that there are at least three mechanisms by which the voltage through a pixel device can be achieved. The first is to increase the operating voltage of the device, the second is by changing the response corresponding to each code value used to represent pixel brightness of the display pixel, and the third by modulating the length of time for which the pixel is on. Any of these techniques, or combination of techniques, will work but may be limited in their dynamic range. These techniques are limited by the operational limits of the device.

[0028] In a preferred embodiment, the invention is employed in a device that includes Organic Light Emitting Diodes (OLEDs), which are composed of small molecule polymeric OLEDs, as disclosed in, but not limited

to, U.S. Patent No. 4,769,292 issued September 6, 1988 to Tang et al., and U.S. Patent No. 5,061,569 issued October 29, 1991 to VanSlyke et al. Many combinations and variations of OLED can be used to fabricate such a device. OLED devices can be integrated in a micro-circuit on a conventional silicon substrate 10 and exhibit the necessary characteristics. Alternatively, OLED devices may also be integrated upon other substrates, such as glass or steel having a pattern of conductive oxide and amorphous, polycrystalline, or continuous grain silicon material deposited thereon. The deposited silicon materials may be single-crystal in nature or be amorphous, polycrystalline, or continuous grain. These deposited materials and substrates are known in the prior art and this invention, and may be applied equally to any micro-circuit integrated on a suitable substrate.

[0029] Hence, as taught in this invention, the integration of reference pixels, the measurement of their performance, and appropriate feedback to the control of the display device can enhance the image quality, lifetime, and power consumption of a digital image display system.

Claims

1. A system for controlling a digital image display device having addressable pixels on a substrate, the pixels having performance attributes, and a control circuit for controlling the pixels of the display device, comprising:

    a) a reference pixel located on the substrate and connected to the control circuit, the reference pixel having the same performance attributes as the pixels in the display;
    b) a measurement circuit connected to the reference pixel to produce an output signal representative of the performance attributes of the reference pixel;
    c) an analysis circuit connected to the measurement circuit to receive the output signal, compare the performance attributes with predetermined performance attributes, and produce a feedback signal in response thereto; and
    d) the control circuit being adapted to receive the feedback signal and control the digital solid-state display device in response thereto.

2. The system claimed in claim 1 wherein the performance attributes measured are one or more attributes selected from the list including charge stored, impedance, current, voltage, and resistivity.

3. The system claimed in claim 1, further comprising a plurality of reference pixels and measurement circuits connected to the analysis circuit.

4. The system claimed in claim 3 wherein the display includes different types of pixels having different performance attributes and the reference pixels include a pixel of each type.

5. The system claimed in claim 4 wherein the types of pixels include pixels of different colors.

6. The system claimed in claim 3 wherein the reference pixels include multiple identical pixels whose results are combined whereby the measured performance attribute is more accurately measured.

7. The system claimed in claim 1 wherein the analysis circuit compares the reference pixel performance attributes to a model of pixel behavior.

8. The system claimed in claim 1 wherein the analysis circuit compares the reference pixel attributes to empirical data relating to the performance of an exemplary display.

9. The system claimed in claim 1 wherein the analysis device compares the reference pixel attributes to historical reference pixel attribute data.

10. The system claimed in claim 1 wherein the measurement circuit is integrated on the same substrate as the reference pixel.

11. The system claimed in claim 1 wherein the analysis circuit is integrated on the substrate.

12. The system claimed in claim 1 wherein the feedback control circuit is integrated on the substrate.

13. The system claimed in claim 1 wherein the measurement circuit measures the current in the reference pixel and the control circuit produces a voltage signal to control the current applied to the pixels of the display.

14. The system claimed in claim 13 wherein the measurement circuit measures the impedance or current of a reference pixel and the control circuit modifies the operational voltage of the display to provide a constant current supply to the display pixels.

15. The system claimed in claim 1 wherein the pixels are organic LEDs.

16. The system claimed in claim 15 wherein the measurement circuit measures the impedance or current of a reference pixel and the circuit modifies the operational voltage of the display to provide a constant current supply to the display pixels to compensate for change in pixel impedance due to change in the OLEDs over time.

17. The system claimed in claim 3, wherein each measurement circuit measures a different performance attribute.

18. The system claimed in claim 1, wherein the reference pixel is also a display pixel.

19. The system claimed in claim 1, wherein the control circuit controls the voltage applied to the entire display device.

20. The system claimed in claim 1, wherein the control circuit controls the voltage applied to groups of pixels on the display device.

21. The system claimed in claim 1, wherein the control circuit modifies the response to the code values used to represent pixel brightness.

22. The system claimed in claim 1, wherein the control circuit controls the time that voltage or charge is applied to the pixels in the display device.

23. A method for controlling a digital image display device having addressable pixels on a substrate, the pixels having performance attributes, and a control circuit for controlling the pixels of the display device, comprising the steps of:

a) providing a reference pixel located on the substrate and connected to the control circuit, the reference pixel having the same performance attributes as the pixels in the display;
b) measuring the output of the reference pixel to produce an output signal representative of the performance attributes of the reference pixel;
c) analyzing the output signal by comparing the performance attributes with predetermined performance attributes, and producing a feedback signal in response thereto; and
d) controlling the digital solid-state display device in response to the feedback signal.

24. The method claimed in claim 23 wherein the performance attributes measured are one or more attributes selected from the list including charge stored, impedance, current, voltage, and resistivity.

25. The method claimed in claim 23, further comprising the steps of providing a plurality of reference pixels and measuring the outputs thereof.

26. The method claimed in claim 25 wherein the display includes different types of pixels having different performance attributes and the reference pixels include a pixel of each type.

27. The method claimed in claim 26 wherein the types of pixels include pixels of different colors.

28. The method claimed in claim 25 wherein the reference pixels include multiple identical pixels whose results are combined whereby the measured performance attribute is more accurately measured.

29. The method claimed in claim 23 wherein the analyzing step includes comparing the reference pixel performance attributes to a model of pixel behavior.

30. The method claimed in claim 23 wherein the analyzing step includes comparing the reference pixel attributes to empirical data relating to the performance of an exemplary display.

31. The method claimed in claim 23 wherein the analyzing step includes comparing the reference pixel attributes to historical reference pixel attribute data.

32. The method claimed in claim 23 wherein the measuring step is performed with a measuring circuit that is integrated on the same substrate as the reference pixel.

33. The method claimed in claim 23 wherein the analyzing step is performed with an analysis circuit that is integrated on the substrate.

34. The method claimed in claim 23 wherein the controlling step is performed by a control circuit that is integrated on the substrate.

35. The method claimed in claim 23 wherein the measuring step is performed by a measurement circuit that measures the current in the reference pixel and the controlling step is performed by a control circuit that produces a voltage signal to control the current applied to the pixels of the display.

36. The method claimed in claim 35 wherein the measuring step includes measuring the impedance or current of a reference pixel and the controlling step includes modifying the operational voltage of the display to provide a constant current supply to the display pixels.

37. The method claimed in claim 23 wherein the pixels are organic LEDs.

38. The method claimed in claim 37 wherein the measuring step includes measuring the impedance or current of a reference pixel and modifying the operational voltage of the display to provide a constant current supply to the display pixels to compensate for the change in pixel impedance due to the aging of the OLEDs.

39. The method claimed in claim 25, wherein each measurement measures a different performance attribute.

40. The method claimed in claim 23, wherein the reference pixel is also a display pixel.

41. The method claimed in claim 23, wherein the controlling step includes controlling the voltage applied to the entire display device.

42. The method claimed in claim 23, wherein the controlling step includes controlling the voltage applied to groups of pixels on the display device.

43. The method claimed in claim 23, wherein the controlling step includes modifying the response to the code values used to represent pixel brightness.

44. The method claimed in claim 23, wherein the controlling step includes controlling the time that voltage or charge is applied to the pixels in the display device.

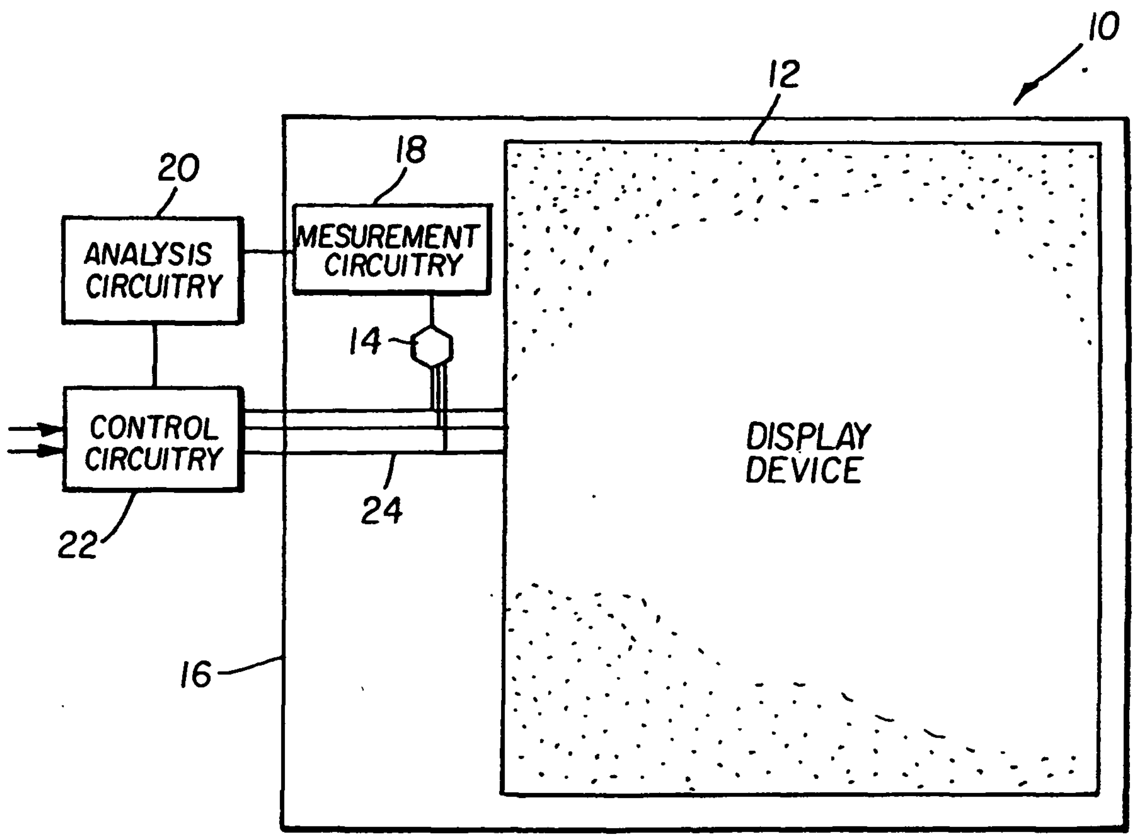
10
12
18
20
ANALYSIS CIRCUITRY
MESUREMENT CIRCUITRY
14
CONTROL CIRCUITRY
24
22
16
DISPLAY DEVICE

FIG. 1

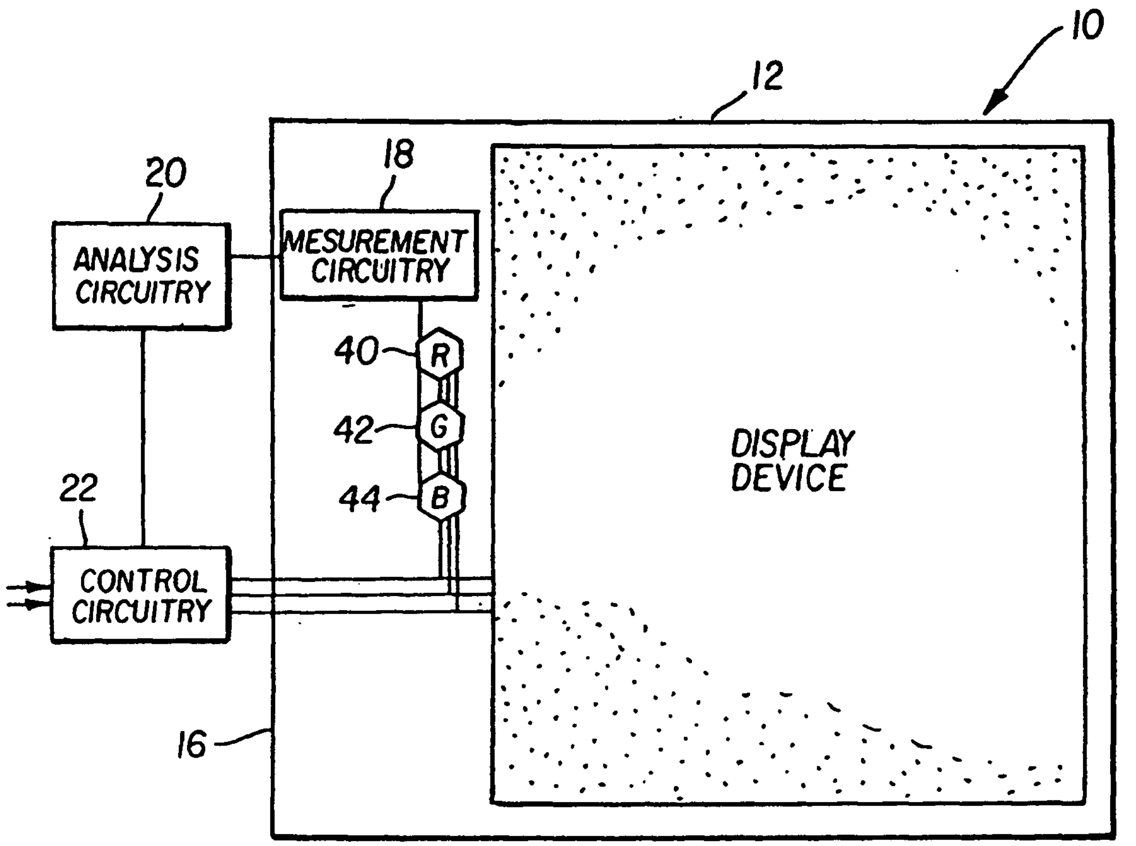
10
12
20
18
ANALYSIS CIRCUITRY
MESUREMENT CIRCUITRY
40
R
42
G
44
B
22
CONTROL CIRCUITRY
DISPLAY DEVICE
16

FIG. 2

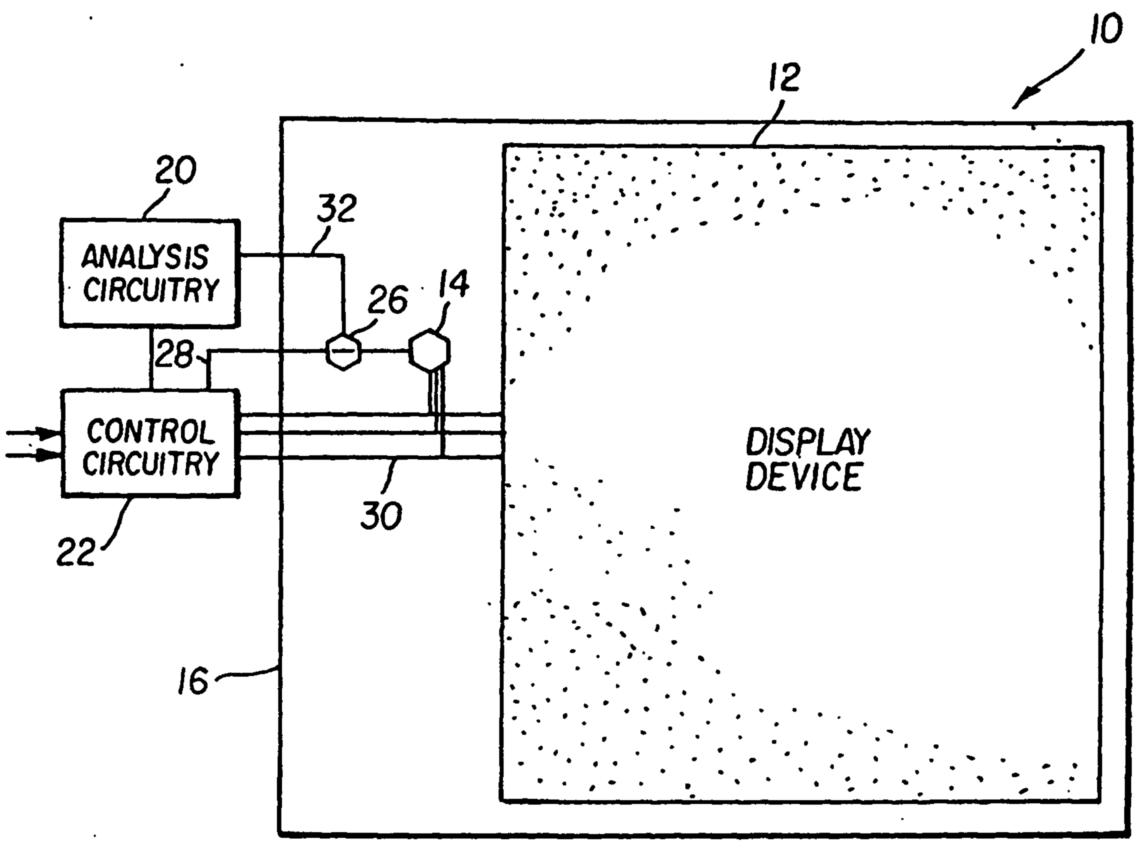
10
12
20
ANALYSIS CIRCUITRY
32
26
14
28
CONTROL CIRCUITRY
DISPLAY DEVICE
30
22
16

FIG. 3